

Microgravity Electron Electric Dipole Moment Experiment with a Cold Atom Beam

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INTRODUCTION

New physics beyond the Standard Model: The small CP violation contained in the Standard Model is insufficient to account for the baryon/antibaryon asymmetry in the universe [Sakharov; 1967]. New sources of CP violation are provided by extensions to the Standard Model. They contain CP-violating phases that couple directly to leptons and from which a large electron electric dipole moment (EDM) may be generated. Observation of an electron EDM would be proof of a Standard Model extension because the Standard Model only allows an electron EDM of less than 10^{-57} C-m (S.I. units; 1 C-m = 1.6×10^{-21} e-cm). A null result, however, constrains models and improving the limit tightens constraints, further restricting the models.

Any discovered new source of CP-violation not contained in the Standard Model will immediately lead to the question “How strongly does it couple to leptons?” The electron EDM experiment

is the experiment that can best answer that question - better than any high energy physics experiment: the electron is stable and it can be precisely probed inside an atom. And the attractiveness of an electron EDM experiments using atoms is that it is sensitive only to a CP violating coupling to leptons - there is no existing effect to be subtracted out.

A microgravity electron EDM experiment can achieve a greater sensitivity than a laboratory experiment because in microgravity the atoms travel slowly, at a uniform velocity, allowing a far greater interaction time, reducing the linewidth and better cancelling motional systematic effects.

Electron EDM experiments using atoms - Electron EDM experiments search for an EDM in a neutral atom (or molecule). The atom establishes a neutral sys-

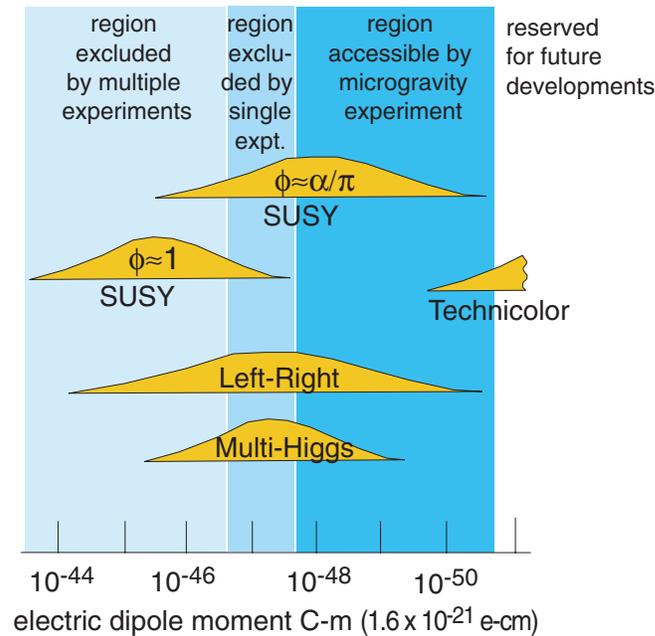


Fig.1: Electron EDM predictions and experimental upper limits in S.I. units (1 C-m = 1.6×10^{-21} e-cm) based upon Fig. 1 of [Pendlebury & Hinds, 2000]. The shape of the theory limit envelopes are not intended to represent any distribution of models.

tem and may provide an enhancement to the electron EDM. This enhancement, R , the ratio of an atomic EDM to a (valence) electron EDM, is a relativistic effect and reaches large values for many high atomic-number atoms. It is 115 ± 15 for the ground state of cesium [Johnson et al., 1986; Sandars; 1966]. Most important, the discovery of an electron EDM, far larger than predicted by the Standard Model, *does not depend upon the error in the calculated enhancement effect being small.*

Electron EDM experiments search for a change in a transition energy upon reversal of an external electric field. The electric field reversal separates a time-reversal (T) violating and parity (P) violating EDM from the T- and P- allowed quadratic Stark effect (Fig. 2). The experiment looks for a change in transition energy between different m_F levels (z projections of the total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$ where $I = 7/2$ is the nuclear spin in Cs and $J = 1/2$ is the electronic angular momentum of the $6^2S_{1/2}$ state). Using both the $F = 4, m_F = -4 \rightarrow m_F = 3$ and $F = 4, m_F = 4 \rightarrow m_F = -3$ transitions to search for the EDM subtracts out the contribution of an incomplete reversal of the electric field

and the first order effect of any residual magnetic field. Other transitions can be used to test for systematic effects. For example, the $F = 4, m_F = -4 \rightarrow m_F = 1$ transition is some thirty times more sensitive to motional systematic effects. This allows one to distinguish a true EDM from the most troublesome systematic effect. In the absence of an EDM or systematic effect, there is no observed effect.

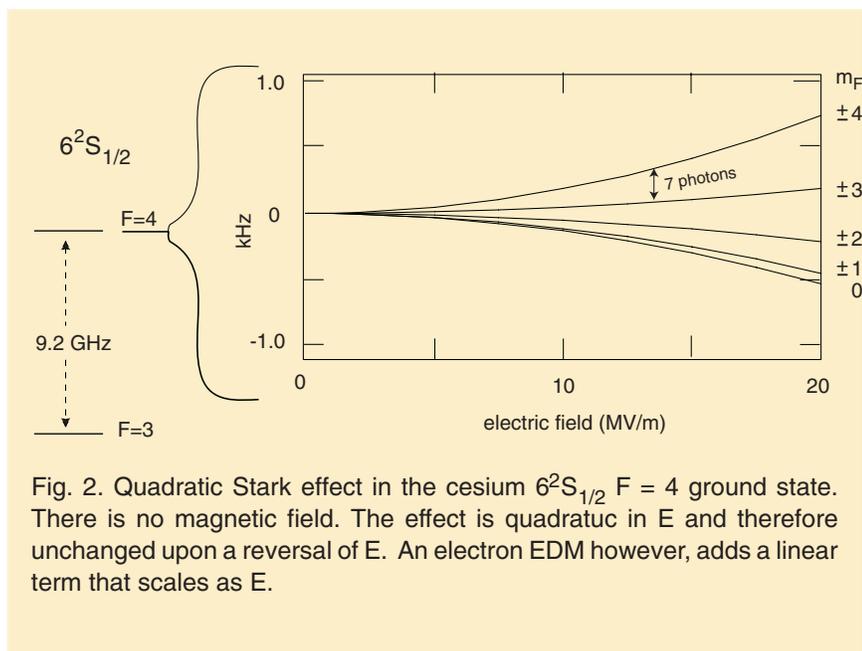


Fig. 2. Quadratic Stark effect in the cesium $6^2S_{1/2}$ $F = 4$ ground state. There is no magnetic field. The effect is quadratic in E and therefore unchanged upon a reversal of E . An electron EDM however, adds a linear term that scales as E .

Since 1964 the majority of electron EDM experiments have used atomic beams in free space, unperturbed by light or frequent collisions; a feature shared by atomic clocks, which they resemble. Not surprisingly, the development of atomic beam EDM experiments has followed the development of atomic clocks and it is expected that EDM experiments will follow laser-cooled atomic clocks into microgravity.

EXPERIMENT

Experimental overview: The signature of the EDM is a net shift in the $m_F = 4 \rightarrow m_F = -3$ and $m_F = 3 \rightarrow m_F = -4$ transition frequencies upon reversal of the electric field. Cesium atoms launched from a magneto-optic trap at 0.1 m/s - 0.2 m/s (and cooled in the moving frame to 2 μK) enter a set of electric field plates with no voltage applied (Fig. 3). The voltage is then applied when the atoms are between the plates. This avoids acceleration of the atoms by electric

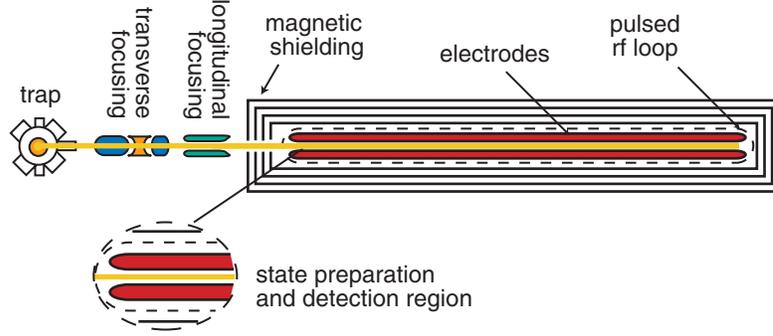


Fig. 3. Schematic of a slow atom microgravity electron EDM experiment

field gradients and defocusing effects from the fringe fields. After one second the field has stabilized and charging currents subsided. The $m_F = +4$, $F = 4$ level of the $6^2S_{1/2}$ state is populated by optically pumping and an oscillatory field, perpendicular to the electric field is applied. This oscillatory field induces a seven photon transition from the $m_F = 4$ level to the $m_F = -3$ level or from the $m_F = -4$ level, to the $m_F = 3$, level (Fig. 2). The experiment will switch between the two sets of initial and final states.

When, in microgravity, the atoms, traveling at 0.2 m/s though the electric field plates, reach the opposite end they will be reflected by the electric field gradient. At 0.2 m/s and in a field of 21 MV/m they will penetrate until the electric field drops by 0.14%. At this point their longitudinal velocity is zero, and they reverse direction and accelerate back to 0.2 m/s.

The reflection is identical for both electric field polarities and the brief 0.14% change in field will not affect the Ramsey resonance or the EDM measurement. As the atoms near the electric field plate entrance the oscillatory field is applied for the second time.

Atoms making the seven-photon transition to the $m_F = -3$ (or $m_F = 3$) of the $F = 4$ level will be optically pumped into the $F = 3$ hyperfine level of the $6^2S_{1/2}$ state. From here they are cycled to the $F = 2$ level of the $6^2P_{3/2}$ state and the fluorescence photons detected. The atoms remaining in the $m_F = 4$ (or $m_F = -4$) level are measure, for normalization, by detecting the fluorescence photons from the cycling transition to the $F = 5$ level of the $6^2P_{3/2}$ state.

Multiple quantum transitions and linewidth: The linewidth is determined by the interaction time (in this case about ten seconds) and the multiplicity of quanta in the transition. The linewidth will be further narrowed by using seven identical photons in the $m_F = 4 \rightarrow m_F = -3$ and $m_F = -4 \rightarrow m_F = +3$ transitions. If the photons are identical (and certain other conditions are met), the linewidth is shared among the 7 quanta and the observed linewidth is narrowed by roughly a factor of 7 [Gould et al., 1969; Gould, 1976; McColm, 1996].

Motional magnetic field effect: To be sensitive to an electron EDM, measurements will be made between levels of different $|m_F|$ which also makes the measurements sensitive to internal and external magnetic fields. The most infamous of these is the motional magnetic field effect.

The motional magnetic field, B_{mot} seen by a neutral atom moving through a static electric field E , with a velocity v , is given (S.I. units, lowest order) by $B_{\text{mot}} = vx/c^2$ where v is the velocity of the atom, E , the electric field, and c , the speed of light. The magnitude of B_{mot} remains

constant upon a reversal of E. However when B_{mot} is added to an external magnetic field, B_0 a component of the magnetic field in the direction of E can change when E is reversed.

The interaction of the atom's *magnetic* dipole moment with this magnetic field component, which changes synchronously with the electric field reversal, mimics an EDM. An external magnetic field, B_0 has here to fore been used to lift the degeneracy between the m_F levels, allowing transitions between them. The elimination of this and other residual magnetic fields (such as those 1 nT fields remaining after magnetic shield deGaussing) will greatly reduce the motional magnetic field effects.

Electric field quantization: The systematic due to motional magnetic fields can be reduced far below experimental sensitivity by making the interaction with the electric field much larger than the interaction with the magnetic field (electric field quantization) [Player and Sanders; 1970.]

The $J = 1/2$ ground states in alkali atoms have very small electric field splittings between the $l m_F$ levels (Fig. 2) and electric field quantization is feasibly only by eliminating all external magnetic fields. Even then, the electric field splittings are too small for resonance transitions in a thermal atomic beam experiments with transition linewidths of several hundred Hz . However the extremely narrow linewidth of a cold atom microgravity experiment makes it feasible to use electric field quantization in the alkali ground state.

ACKNOWLEDGMENTS

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